

# A Possibility to Observe Short-Range NN Properties in the Deuteron Breakup $pd \rightarrow ppn$

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Quasi-binary reaction of the deuteron breakup  $p + d \rightarrow (pp) + n$  with the final proton-proton pair ( $pp$ ) in the  $^1S_0$  state is analyzed at initial energies 0.5–2 GeV in the kinematics of backward elastic  $pd$ -scattering  $pd \rightarrow dp$ . On the basis of the main mechanisms of the  $pd \rightarrow dp$  process, including initial and final state interaction, we show that unpolarized cross section and spin observables of this reaction exhibit important properties of the half-off-shell  $pp(^1S_0)$ -scattering amplitude, which are relevant to the nucleon-nucleon interaction at short distances.

*Key words:* deuteron breakup, nucleon-nucleon interaction

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The short-range structure of the lightest nuclei is related to fundamental problems of the theory of strong interactions. At present the main task consists in a clear experimental observation of this structure and determination to what limiting values of the intrinsic nucleon momenta  $q$  the traditional description of nuclei in terms of nucleons is valid. In the framework of the impulse approximation (IA), available inclusive experimental data on spin averaged cross section for deuteron disintegration  $dp \rightarrow p(0^\circ)X$ ,  $d^{12}\text{C} \rightarrow p(0^\circ)X$  (see [1,2] and references therein) are compatible with the realistic deuteron wave functions at low internal momenta  $q < 0.3$  GeV/c only. At higher momenta a systematic deviation from the IA is observed [3]. This disagreement is very strong for the tensor analyzing power  $T_{20}$  of these reactions. On the contrary,

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the recent JLab data on  $T_{20}$  in the elastic ed-scattering [4] demonstrate that the similar impulse approximation with standard wave function, such as RSC [5], Paris [6] or Bonn [7], is in fair agreement with the experiment over the interval of transferred momenta  $Q^2 = 0 - 1.7 \text{ (GeV/c)}^2$ , i.e. for the same internal momenta  $q \sim Q/2 \sim 0.7 \text{ GeV/c}$  as probed in pd-interaction. On the whole, such difference between the ed- and pd- interactions can be attributed to a presence of specific for pd-collisions mechanisms, in particular, to the exotic like  $N^*$ -exchanges in the  $u$ -channel [8,9] or three-baryon resonances in the  $s$ -channel [10]. The deviation from the IA in exclusive data on the reaction  $p + d \rightarrow p + n + p$  can be explained in part by rescatterings in the final state [11]. Other ordinary mechanisms like double pN-scattering with excitation (and de-excitation) of nucleon isobars ( $\Delta, N^*$ ) in the intermediate states can give a large contribution also. The latter mechanisms are less sensitive to the short-range structure of the deuteron than the IA mechanism. At present a correct treatment of these mechanisms is a nontrivial problem for theory, as it can be seen from the analysis of backward elastic pd- scattering in GeV region [10,12–14].

To minimize screening effects caused by excitations of nucleons inside the deuteron due to its interaction with incident proton we propose to study the deuteron breakup with formation of the final spin singlet  $(NN)_s$  pair in the  $^1S_0$  state in kinematics of the backward (quasi)elastic pd-scattering. These are

$$p + d \rightarrow (pp) + n \quad (1)$$

and  $n + d \rightarrow (nn) + p$  reactions at small relative energy of the final NN-pair,  $E_{NN} = 0 - 3 \text{ MeV}$  [16]. According to [17], the presence of the  $pn(^1S_0)$ -pair in the final state provides a considerable suppression of the amplitude of the  $\Delta$ -isobar mechanism due to isospin factor of  $\frac{1}{3}$  in comparison with the elastic backward pd-scattering. We note here that the same suppressing isotopic spin factor is effective for broader class of diagrams than established in [17]. Furthermore, we take into account initial and final state interactions in the eikonal approximation. In addition, we present the results of calculation of some spin observables.

The dynamics of the reaction (1) is discussed here by analogy with the backward elastic pd-scattering [10,12] taking into account one nucleon exchange (ONE), single  $pN$  scattering (SS) and double  $pN$  scattering with excitation of the  $\Delta$  isobar in the intermediate state (figure 1 (*a-c*)). As was shown in [14,15], at low kinetic energies of the proton beam  $T_p \sim 0.2 - 0.3 \text{ GeV}$  the coherent sum of ONE+SS describes energy and angular dependence of the cross section and explains qualitatively vector and tensor analyzing powers of the  $pd \rightarrow dp$  process in backward hemisphere. At higher energies  $T_p = 0.4 - 1.0 \text{ GeV}$  the  $\Delta$ -mechanism dominates. A  $\pi + \rho$  exchange model of the  $NN \rightleftharpoons \Delta N$  amplitude [18] describes well the experimental cross section of the  $pp \rightarrow pn\pi^+$  reaction

[19] in the  $\Delta$ -region. The ONE+ $\Delta$ +SS model with the same  $\Delta$ -amplitude as in [18], allows one to describe the energy dependence of the  $pd \rightarrow dp$  cross section in the interval of energies  $T_p = 0.5 - 2.5$  GeV at  $\theta_{cm} = 180^\circ$ .

A detail formalism for the amplitude of the reaction  $pd \rightarrow (NN)N$  in the framework of the ONE+SS+ $\Delta$  model can be derived from the  $pd \rightarrow dp$  formalism of Refs. [10,14]. For this aim one should make the following substitution into the matrix elements

$$|\varphi_d \rangle \rightarrow \sqrt{m} |\Psi_k^{(-)} \rangle, \quad (2)$$

where  $|\varphi_d \rangle$  is the deuteron final state in the  $pd \rightarrow dp$ ,  $m$  is the nucleon mass and  $|\Psi_k^{(-)} \rangle$  is the scattering state of the final NN-system at the relative momentum  $k$  in the  $N + d \rightarrow (NN) + N$  reaction. Since the S-wave gives the main contribution to the singlet  $(NN)_s$  state at  $E_{NN} < 3$  MeV, one should omit the D-component of the final deuteron state  $|\varphi_d \rangle$  in the  $pd \rightarrow dp$  formalism [10,14] when making the substitution (2). Thus, one has to insert into the upper vertex of the ONE diagram (figure 1 (a)) the half-off-shell amplitude of  $pp$ -scattering in the  $^1S_0$  state,  $t_s(q, k)$ . This amplitude is shown in figure 2 as a function of the off-shell momentum  $q$  at different values  $E_{pp} = \frac{k^2}{m}$ . The first node of  $t_s(q, k)$  at  $q = 0$  is caused by the Coulomb repulsion, whereas the second node at  $q \sim 0.4$  GeV/c arises due to short-range repulsion in the  $NN$  potential of strong interaction. A similar node, available in the deuteron S-wave function in the momentum space  $u(q)$  at  $q \sim 0.4$  GeV/c, can be connected indirectly to the null of the measured deuteron charge formfactor  $G_C(Q)$  at the transferred momentum  $Q \sim 4.5$  fm $^{-1}$  [23,4]. The node of  $u(q)$  was not yet observed directly in any reactions with the deuteron due to large contribution of the deuteron D-state. An important feature of the reaction (1) is a possibility to display the node of the amplitude  $t_s(q, k)$  straightforwardly in the cross section. One can see it from the following formula for the cross section of the reaction (1) derived for the ONE mechanism (figure 1 (a))

$$\frac{d^5\sigma}{dp_1 d\Omega_1 d\Omega_2} = K \left[ u^2(q) + w^2(q) \right] |t_s(q', k)|^2, \quad (3)$$

where  $w(q)$  is the D-wave of the deuteron state,  $K$  is the kinematical factor; the indices 1 and 2 refer to the final protons which are detected in the forward direction. Using relativistic kinematics for the ONE amplitude [16], one can find that the node of  $t_s(q', k)$  at  $q' \sim 0.4$  GeV/c corresponds to the energy  $T_p \sim 0.7$  GeV at the neutron scattering angle  $\theta_{cm} = 180^\circ$ .

The isospin factors for the reaction  $p + d \rightarrow (pn)_s + p$  are discussed recently in [15]. As was shown there, an additional isospin factor of  $\frac{1}{3}$  arises for the  $2\pi$  exchange mechanism of this reaction in comparison with the  $pd \rightarrow dp$  process. This mechanism includes, in particular, the  $\Delta$ - and  $N^*$ - excitations in the intermediate state. On the contrary, for the ONE mechanism the isospin factor

equals 1.

Rescatterings in the initial and final states are taken into account here for the ONE-mechanism using an eikonal version of the distorted wave Born approximation (DWBA). This method was successfully applied in [21] to the backward elastic  $p^3\text{He}$ -scattering at  $T_p \geq 1$  GeV in the framework of the np-pair exchange mechanism. Another application was done to the backward elastic  $pd$  scattering within the ONE mechanism [22]. Due to rescatterings one obtains three other ONE diagrams depicted in figure 1(*d-f*) in addition to the plane wave one (figure 1(*a*)). Assuming elastic rescattering to dominate, the pp-pair is considered here as a quasibound system with a fixed internal energy  $E_{pp}$ . Since the SS- and  $\Delta$ -mechanisms are less important they are treated in the plane wave approximation.

Numerical calculations are performed here with the RSC potential. As was shown in [16], the result with the Paris potential obtained for the ONE-mechanism is very similar. The results for the cross section are shown in figure 3(*a*). One can see from this figure that the  $\Delta$  and SS- contributions have their maxima at  $T_p \sim 0.6$  GeV, i.e. close to the dip of the ONE cross section. Nevertheless the coherent sum ONE+SS+ $\Delta$  demonstrates well pronounced dip in the cross section. The ONE mechanism dominates at  $T_p < 0.5$  GeV and above 1 GeV. At  $T_p > 1$  GeV the ONE+ $\Delta$ +SS-model predicts a plateau in the cross section as a function of the initial energy at  $\theta_{cm} = 180^\circ$ . This plateau manifests the  $T_p$  dependence of the right hand side of Eq. (3).

The role of the  $\Delta$ -mechanism is important mainly in the node region  $T_p \sim 0.7$  GeV, but becomes negligible at  $T_p > 1$  GeV. A minor contribution is expected also at  $T_p > 1$  GeV from excitation of heavier nucleon isobars  $N^*$  because of the same suppressing isospin factors as for the  $\Delta$ -isobar<sup>2</sup>. As seen from the  $E_{pp}$  dependence of  $t_s(q, k)$  (figure 2), the maximal value of the cross section of the reaction (1) is expected at  $E_{pp} = 0.3 - 0.7$  MeV. At  $E_{pp} < 0.3$  MeV the cross section decreases rapidly due to Coulomb repulsion in the pp-system. At higher relative energies  $E_{pp} \sim 5 - 10$  MeV the role of nonzero orbital momenta  $l \neq 0$  in the half-off-shell NN-amplitude increases and makes the node of the S-wave amplitude  $t_s(q, k)$  be non-visible in the cross section [16].

Rescatterings in the initial and final states fill in in part the ONE-minimum of the cross section. Nevertheless, this minimum is well pronounced (figure 3(*a,c*)). As shown in figure 3(*b*), rescatterings produce a remarkable structure in  $T_{20}^{ONE}$  in the region of the node of the half-off-shell NN-amplitude. On the contrary, in the elastic  $pd \rightarrow dp$  process the rescatterings do not change practically the tensor analyzing power  $T_{20}^{ONE}(180^\circ)$  since in this case the node in the

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<sup>2</sup> An only exclusion might be the  $N^*(1535)$ -isobar strongly coupled to the  $\eta$ -meson. The maximum of the  $N^*(1535)$ - contribution to the reaction (1) is expected at  $T_p \sim 1.6$  GeV.

$pn \rightarrow d$  vertex of the ONE-diagram is hidden by the D-wave contribution [14]. Therefore rescatterings in the reaction (1) and interference between the ONE and other mechanisms give an additional signal for the presence of the node. A similar irregular behaviour demonstrates the spin-correlation parameter  $C_{yy}$  depicted in figure 2( $d$ ) (for the definition see [24]).

The reaction (1) was not yet investigated experimentally. Available experimental data on the formation of the singlet  $(pn)_s$  pair in  $pd$  interactions are obtained in semiinclusive experiments [2,20]. The energy resolution in [2,20] was not enough high to observe the above discussed properties of the  $pd \rightarrow (pn)_s p$  channel. The only exclusive measurement [25] of the reaction  $pd \rightarrow pnp$  at 585 MeV displays a very small fraction (about a few percent) of the singlet contribution [26]. Direct measurement of the singlet channel in the reaction (1) is planned at COSY [27].

In conclusion, we have found that the role of the ONE mechanism increases considerably in the reaction (1) in comparison with the process  $pd \rightarrow dp$ . It caused i) by the isotopic spin factors suppressing the diagrams which are relevant to excitation of the nucleon isobars in the intermediate state of this reaction and ii) by dominance of the S-state in the pp-system at low  $E_{pp}$ . As a result, we found within the DWBA ONE +  $\Delta$  + SS model that the node available in the standard potential picture of the half-off-shell  $pp(^1S_0)$  scattering amplitude appears as an irregularity in the behaviour of the observables. Thus, the reaction (1) provides new qualitative criteria to clarify the role of nucleon degrees of freedom in NN-system at short distances.

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